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METHOD AND SYSTEM FOR CREATING MODELS FROM IMAGERY

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METHOD AND SYSTEM FOR CREATING DENTAL MODELS FROM IMAGERY

FIELD OF THE INVENTION

5   The invention relates generally to the field of dental imagery, and in particular to a method and apparatus for effecting imagery of a prepared cavity in a tooth followed by automatic generation of a model to control automatic fabrication of a dental inlay for the cavity.

BACKGROUND OF THE INVENTION

10   The invention described herein relates generally to the following conventional situation. A dentist prepares a cavity of a decayed tooth to allow its restoration by means, e.g., of an inlay or a crown. After the preparation has been rendered, an impression of the cavity is taken, and is ordinarily sent to a dental laboratory. Contrary to such conventional techniques, there are different and

15   more recent techniques which alleviate the role of the dental laboratory and fabricate the desired restorative piece in the dental office. In particular, the prepared cavity is registered by an electro-optic scan head. The data thus obtained can be complemented by operator input, using techniques from the CAD (Computer-Aided-Design) domain, and the final piece is fabricated with the aid of

20   a miniature NC (numerical control) grinding machine.

U.S. Patent No. 4,837,732 (Brandestini et al) describes a method for a dentist to record the shape in situ of teeth prepared for repair. The method involves the acquisition of data defining the three-dimensional shape of prepared

25   teeth and their immediate vicinity. First, a video display shows a live image from a scan head, and the scan head is manually oriented relative to the prepared teeth while observing the image of the teeth on the video display. Thereafter the data produced by the scan head in a selected orientation generates corresponding depth and contrast images, and a depth image is processed based on the contrast image.

30   This method also includes the step of superimposing graphic markers on the image displayed on the video display to facilitate an on-line alignment of the teeth displayed in the live image with reference data from previous data acquisitions.

The drawback to this method from the prior art is that it incorporates a registration scheme that can later interfere with the quality of the results, and also requires that the dentist be able to hold the scan head almost perfectly still at a specific point in the procedure. More specifically, the artifacts typically due to the 3D registration scheme (such as fringe, speckle and/or venetian blind effect) are cited in the patent as "intolerable and must be eliminated" since phase angle differences are used for measurement of the depth. Furthermore, the patent cites a need for a "quasi-instantaneous 3D acquisition following a trigger release", the essential condition being that the orientation of the scan head must not change between the search and acquisition modes.

What happens in Brandestini et al is that the 3D result is *overlaid* on the search image allowing the dentist to verify the result. What is needed, however, is a system in which the 3D results are *projected* into the image using the projective equations of photogrammetry. This would cause the results to appear as if they were actually present in the scene at the time of image acquisition, allowing a much more accurate and precise evaluation.

Previous photogrammetric-based approaches, however, (see, e.g., U.S. Patent No. 5,372,502) have not been too successful for a number of reasons. For example, such approaches have not been successful because it is hard to determine the exact relationship between the camera and the object. Moreover, it is also hard to precisely measure the object because teeth are fairly uniform in color and have little texture (which is in part why it is hard to determine the relationship discussed above).

SUMMARY OF THE INVENTION

The present invention is directed to overcoming one or more of the problems set forth above. Briefly summarized, according to one aspect of the present invention, a method (and system) for creating a dental model from a series of images of an intra-oral object includes the steps of (a) capturing a series of images of the intra-oral object from a plurality of capture positions, where the object includes common surface features and a control target arranged with respect to the object to provide control features; (b) measuring the control features from the control target imaged with the images of the object; (c) analytically

generating a 3-dimensional model of the object by photogrammetrically aligning the measurements of the control features, thereby providing a photogrammetrically-aligned 3-dimensional model of the object while reducing image errors due to the variable orientation of the capture positions; and (d)

5 adjusting the photogrammetrically aligned 3-dimensional model of the object by aligning the common features of the model to like features on the image of the object, thereby producing an aligned dental model from the series of images. In practice, the last stage involves the application of a 3-dimensional morphing algorithm to correct for the misalignment.

10 The principal advantage of the invention is that the use of photogrammetric projection methods and adjustment to control eliminates the need for a registration scheme, such as that used in Brandestini et al, which projects stripes of light onto the target and can result in unacceptable artifacts. Furthermore, under the present invention, there is no need to restrict the

15 acquisition of the image(s) to a "quasi-instantaneous" state, as phase information is not used.

It becomes possible to measure the exact relationship between the camera and the intra-oral object because the use of a target provides something to measure, thus allowing the determination of the relationship between the camera

20 and target. The use of 3D morphing addresses the matter of precisely measuring the object itself by projecting the data that is available into the picture and letting one see how well it fits – in the 3D object space. If correct, the model of the tooth should "fit" the tooth "skin tight".

These and other aspects, objects, features and advantages of the

25 present invention will be more clearly understood and appreciated from a review of the following detailed description of the preferred embodiments and appended claims, and by reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

30 FIG. 1 is a block diagram of the method for creating dental models from imagery according to the invention.

FIG. 2 is a perspective diagram of a target useful with the method described in Figure 1.

FIG. 3 is a block diagram of a morphing technique utilizing a database of generic tooth models.

FIG. 4 is a diagram of a dental system that utilizes the method shown in Figure 1.

DETAILED DESCRIPTION OF THE INVENTION

Because dental image processing systems and methods are well known, the present description will be directed in particular to elements forming part of, or cooperating more directly with, apparatus and method in accordance with the present invention. Elements not specifically shown or described herein may be selected from those known in the art. Certain aspects of the embodiment to be described may be provided in software. Given the system as shown and described according to the invention in the following materials, software not specifically shown, described or suggested herein that is useful for implementation of the invention is conventional and within the ordinary skill in such arts. This is particularly true given the advanced technical state of conventional photogrammetry and the well-understood current automation of the photogrammetric process.

Referring initially to Figure 4, a preferred embodiment of the invention is implemented in a system including an intra-oral camera 2, a computer system 3 including instructions for implementing the invention and a machine tool 4. In the schematic shown in Figure 4, it should be understood that the interconnections between the camera 2, the computer system 3 and the machine tool 4 are shown by arrows, and therefore not specifically indicated. These interconnections may take various forms, such as a cable or any other electromagnetic connection (such as an rf transmission), or the manual transfer of data from machine to machine. The camera 2 may be any type of conventional dental camera that is capable of capturing a reasonably high resolution image of an intra-oral object, such as the teeth 4; a preferred example is the intra-oral camera disclosed in commonly assigned, copending U.S. Patent Application Serial No. 09/796,239, entitled "Intra-Oral Camera with Integral Display", filed February 28, 2001 in the names of J.P. Spoonhower, J.R. Squilla and J.T. Boland, and which is incorporated herein by reference.

The camera 2 is hand held by the dentist and several images are captured of the teeth; it is understood, however, that the orientation of the camera relative to the teeth will vary from one image to the next. The elimination of the effect of these different orientations on the subsequent measurements is one

5   feature of the invention. The digitized data from the camera 2 is transferred to the computer system 3 for processing. The methodology of the invention is implemented by the computer system 3 in its processor 5, and the imaging results may be interactively displayed on a monitor 6. An operator using a keyboard 7 and/or a mouse 8 can manipulate a cursor 9 to perform measurements of the type

10   that will be subsequently described. The output from the computer system 3 is a digitized three-dimensional surface pattern that is transferred to the machine tool 4 as a tool path program for the fabrication of a dental mold or a restorative piece. The program will direct a milling cutter 10 in the milling of the tooth mold or the restorative piece 11 from a suitable substrate, for example, ceramic or any other

15   suitable machinable material.

The dental imaging method according to the invention employs a mensuration method that utilizes photogrammetric projection, analytical adjustment to control and three-dimensional morphing to develop accurate dental models. Mensuration, in this instance, refers to a measurement process involving

20   several steps: (1) the identification of control points on the digitized image, (2) the stereoscopic transfer of those points to the overlapping images upon which they appear, and (3) the actual measurement of the image coordinates of the control points.

Photogrammetry generally is the science of measuring graphically

25   by means of light, and more specifically the science of obtaining reliable measurements by means of photographs or other forms of imagery, such as electronic sensing by a sensor (see generally Manual of Photogrammetry, Fourth Edition, American Society of Photogrammetry, 1980). Photogrammetric projection refers to an image projection that uses an analytical representation of

30   the physical model that describes the imaging process of the sensor. The term projection specifically refers to the concept of a light ray projecting from the intra-oral object, through the sensor lens, to the image plane, in this case using the

physical model of the imaging process to determine where the points will be located.

Analytical adjustment to control refers to the process of correcting the set of parameters which describe the physical model, to a subset of known, or control, parameters. A least squares adjustment process is typically applied to a set of normal equations, derived from a set of linearized condition equations, which in turn are partial derivatives of the image coordinates with respect to the total parameter set. Details of the least squares process is well known to those of ordinary skill in this art and described, e.g., in the Manual of Photogrammetry, Fourth Edition, op. cit., pp. 77 – 88, which is incorporated herein by reference.

Three-dimensional morphing refers to the process of adjusting a 3-dimensional, object model to an image(s) of the object. This is accomplished by projecting a hypothesized 3-dimensional model of the object into an existing image (through the analytical physical model referred to above), detecting the misalignment between the true image and the projected, object model-derived image, and making corrections to the object model (which is then re-projected) to improve the fit. Techniques for three-dimensional morphing are well known in the art and will not be described in detail herein. For further information, reference may be made to articles by Frederic Pighin et al., "Synthesizing Realistic Facial Expressions from Photographs", in *Computer Graphics Proceedings, Annual Conference Series*, 1998, pp. 75 – 83 and by Takaaki Akimoto et al., "Automatic Creation of 3D Facial Models", in *IEEE Computer Graphics & Applications*, September 1993, pp. 16 – 22. In these articles, the specifics are directed toward facial models, but the technology application to teeth models would be the same.

Referring to Figures 1 and 2, the method according to the invention is shown, in which multiple images 12 of an intra-oral object (one or more teeth 14) are initially captured from several different aspects and/or positions by the camera 2. For each image, one or more of the teeth 14 (e.g., a tooth 14a) includes a control target 16, as shown in Figure 2. (In practice, the tooth is typically either the original, unprepared tooth or the tooth as prepared (i.e., a tooth stump) for the restorative procedure.) The target 16 is rigid material, of saddle form, which rests on the tooth 14a with length C along the side of the tooth. (Although not shown

as such in Figure 2, the control target 16 could span several teeth, such as both teeth 14a and 14b.) Lengths A, B, C, and D are known, and may be unequal. Angles included by the vertices 18 are also known; as will be described, the vertices 18 are the aforementioned known, or control, parameters that are used in

5   the analytical adjustment to control. Several targets may be constructed in varying sizes to accommodate different size teeth. Generally, several images are taken from several different aspects/positions as the basis for a 3-dimensional view of the intra-oral object, including both the control parameters and certain common features on the tooth, such as the cusps and valleys describing the natural

10   topographic surface of the tooth (or the tooth stump, if the intra-oral object is a prepared tooth).

The mensuration process involves the measurement of common features or parameters (the cusps and valleys) in a feature measurement stage 20 and the measurement of control features or parameters (the vertices 18) on the

15   target 16 in a control measurement stage 22. There are several ways to take these measurements. Referring to Figure 4, these measurements may be interactively taken by an operator positioning the cursor 9 over the respective features on each of the multiple images 12 as they are displayed on the monitor 6; the coordinates of each measurement are then captured by the processor 5. Alternatively, the

20   processor 5 may employ appropriate conventional image processing algorithms to automatically locate each of the features; this may involve image enhancement and other feature improvement algorithms, as necessary. The measurements are then processed in a photogrammetric adjustment stage 24 in order to compute the object-space coordinates of any object point which is imaged in the multiple

25   overlapping images from varying camera orientations; this process utilizes the aforementioned least squares process described in the Manual of Photogrammetry, Fourth Edition, op. cit. Basically, this is a multiray stereo intersection process that is used to locate each image point relative to the camera position. The result is a 3-dimensional model 26 of the tooth that has been

30   processed with an analytical representation of the physical model which represents the imaging process of the sensor that captured the images.

However, the imaging device is usually a handheld camera that does not make a perfect geometric representation of the object, which creates

errors due to the lack of certainty of knowledge about the image positions. One of
the features of the invention is to tackle the problem of eliminating these errors,
i.e., the camera's variability in orientation, before attempting to correct for errors
in the actual model of the tooth. In this manner, the requirement (and problem)
5   noted in the prior art, namely, that the scan head or imaging device must be held
perfectly still, can be avoided. Therefore, an analytical adjustment using the
control points (the vertices 18) to correct the estimates is made by analytically
projecting the 3-D model 26 in an analytical projection stage 28 into an existing
image (one of the multiple images 12), determining the misalignment of the
10   control points (the vertices 18) between the model and the image in a
misalignment stage 30 and refining the photogrammetric adjustments in a
refinement stage 32 if the misalignment is unacceptable (decision 34). The
projection is an analytical process, meaning that it is accomplished
mathematically, and the determination of misalignment may be accomplished
15   interactively (by using the cursor 9) or automatically with appropriate image
processing algorithms. It is helpful to understand that this projection process
utilizes the physical model representing the imaging process, therefore differing
from a simple overlay of the 3-D model onto the image. Once these corrections
are made, the variability in the model caused by the various camera orientations is
20   reduced to an acceptable level, if not eliminated.

Once the control alignment is acceptable, the slopes and curves
between the cusps and valleys in the model should either match, or be made to
match, the corresponding features in the image of the tooth. Thus, it is necessary
to determine the remaining misalignment of the model relative to the actual image
25   in a misalignment determination stage 36, that is, to determine the misalignment
(if any) of the common features in the model with respect to the same features in
the actual image. If misalignment is present (decision 38), a three-dimensional
morphing stage 40 is initiated for adjusting the 3-dimensional object model in an
adjustment stage 42 to an image(s) of the object. (This changes the 3-dimensional
30   position of points in the model without affecting the prior alignment adjustment
regarding the camera orientation.) This is accomplished in a projection stage 44
by projecting the hypothesized 3-dimensional model of the object into one of the
existing images (through the analytical physical model referred to above) of the

intra-oral object. Then, the misalignment between the true image and the projected, object model-derived image is detected in a misalignment stage 46. If the misalignment is acceptable (decision 48), the process is ended; otherwise, corrections are made to the object model in the stages 40 and 42 (which is then re-

5   projected) to improve the fit.

At this point, an acceptable model of the tooth has been generated and may be used in subsequent processing, such as in the fabrication of the desired restorative piece, either in a laboratory or in the dental office by use of the machine tool 4. It should be understood that in addition to teeth, other dental

10   prosthetics can be modeled in accordance with the invention, including without limitation bridges, veneers and other dental restorative units. Moreover, various other types of fabrication may be employed without limitation in addition to milling or cutting, such as injection molding.

Figure 3 represents an alternative method for adjusting the 3-

15   dimensional object model to an image(s) of the intra-oral object, that is, an alternative method to the logic represented by the elements 40-48 of Figure 1. More specifically, in the alternative approach of Figure 3, generic 3D models from a database 50 of such items may be used in addition to, or as a substitute for the 3D model provided in the elements 40-48. This approach specifically

20   addresses the issue around difficulty in accurately measuring the cusps and valleys, as they may not be as well defined as the target vertices, by allowing a generic tooth model to be used instead. This essentially means that in Figure 1, the 3-D model 26 can be eliminated, or more correctly, reduced to only creating a 3D model of the target (vs. the tooth and target) and proceeding from there.

25   The invention has been described with reference to a preferred embodiment. However, it will be appreciated that variations and modifications can be effected by a person of ordinary skill in the art without departing from the scope of the invention.

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PARTS LIST

2	camera
3	computer system
4	machine tool
5	processor
6	monitor
7	keyboard
8	mouse
9	cursor
10	milling cutter
11	restorative piece
12	multiple images
14	teeth
14a	tooth
14b	tooth
16	control target
18	vertices
20	feature measurement stage
22	control measurement stage
24	photogrammetric stage
26	3-D model
28	projection stages
30	misalignment stage
32	refinement stage
34	decision
36	misalignment stage
38	decision
40	3-D morphing stage
42	adjustment stage
44	projection stage
46	misalignment stage
48	decision

50   database of 3-D models